VARIABILITY IN POSTTREATMENT ARCH SHAPE – IS IT RELATED TO STABILITY?

A Thesis

by

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ABSTRACT

Introduction: The aim of the present study was to evaluate the variability in posttreatment arch shapes, and investigate its relation to the long-term stability of dentition.

Materials and Methods: The sample consisted of 100 previously treated orthodontic patients from 3 private practices, evaluated at posttreatment (mean age 15.6 ± 3.1 years old; 51 extraction, 49 nonextraction) and again at postretention (mean age 33.4 ± 7.7 years old). Three dimensional orthodontic models were digitized to determine arch shape, dimensions, and malalignment. Arch shape was determined using fourth-order polynomials best fit to the digitized arch. Malalignment was based on TSALD and incisor irregularity.

Results: Malalignment changes were not significantly different between groups. TSALD and incisor irregularity were significantly correlated. Contact angles were smallest between canines and lateral incisors. They were significantly smaller in extraction cases than nonextraction cases. Extraction cases also had significantly smaller posttreatment arch dimensions. Factor analyses demonstrated that both males and nonextraction arch shapes were broader at posttreatment than female and extraction arches, respectively. Broader posterior arch shapes were significantly correlated with fewer changes in posttreatment crowding.

Conclusions: Orthodontic treatment can be very stable long term. Sex and treatment modality are related to arch shape. Broader posterior arches, together with larger contact angles, indicate more stable arches.

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NOMENCLATURE

II	Incisor Irregularity
mm	millimeter
TSALD	Tooth-size-arch-length-discrepancy

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

There are more people who have Class I malocclusions than those who have a normal occlusions.[1] Approximately 40% of the untreated population 15 to 50 years of age have incisor irregularities that justify a need for treatment.[2] Dental malalignments worsen over time in untreated individuals, even for those who start with normal occlusions.[3-7] Malalignment similarly worsens in patients who have been treated with orthodontic therapy, and these changes appear to be independent of the pretreatment severity.[8-10]

Dental malalignment is predominately quantified by two different measurements. Tooth-size-arch-length-discrepancy, or TSALD, is a measurement of dental crowding. TSALD represents the difference between tooth size and arch space available. Incisor irregularity, or II, is a measurement of dental irregularity.[11] II is measured as the sum of distances between the contact points of adjacent teeth. While related, these measurements are inherently different and should not be used interchangeably.[10, 12]

Various factors have been shown to be associated with dental malalignment.[9] Early malalignment is a due to the loss of arch space. When space is present in the arch, transseptal fibers will attempt to regain tooth contacts by closing the space.[13, 14] This results in early malalignment when the space created is attributed to early exfoliation of primary teeth, disruptions in the emergence pattern of permanent teeth, and tooth impactions.[15-21] Late malalignment, on the other hand, is due to tooth movements that lead to contact displacements. These contact displacements are related to the vertical eruption of teeth during growth, an anterior componenet of force during occlusal loading, and tight interproximal restorations.[10, 22-28] The greatest contact displacement occurs between the canine and lateral incisor.[9, 29] This contact is at the greatest curvature of the arch. Narrower arch shapes make a sharper transition at this juncture, while broader arches make a more gradual transition. The question arises as to whether or not arch shape plays a role in the stability of contacts, and thus dental malalignment.

In 2013, Myser et al.[10] reported a correlation between shape of the arch and the long-term stability of orthodontic treatment. Their results suggested that the canine to lateral incisor was the most vulnerable contact point to displace, leading to malalignment. Increases in both TSALD and incisor irregularity were related to more tapered arch shapes. While these results were indicative of a relationship between arch shape and malalignment, the study relied on angular and linear measurements to only describe anterior arch shape. Better ways to quantify arch form have been utilized that account for total arch shape, asymmetries, and a higher level of customization.

AlHarbi et al.[30] compared various methods of mathematical curve fitting and found that fourth-order polynomials best fit dental arch forms. Their natural curvature and ability to account for asymmetries make them the ideal candidate for evaluating posttreatment and postretention arch shapes. To date, little research exists on a relationship between arch shape and dental malalignment. Kageyama et al.[31] utilized fourth-order polynomials to compare arch shapes in various facial types, but they did not investigate the relationship between shape and malalignment.

The purpose of the present study is to investigate the variability in posttreatment arch shapes and its relationship to long-term stability in both extraction and nonextraction patients. This will be performed using the posttreatment and postretention casts of previously treated orthodontic subjects. It is the aim of this study to investigate whether treating orthodontic patients with broader arch shapes, while maintaining proper orthodontic treatment values such as teeth over basal bone and no excessive increase in intercanine

2. LITERATURE REVIEW

Class I malocclusion is the most prevalent type of dental malalignment. Over 55% of the US population has some degree of dental crowding in the maxillary arch. In the mandibular arch, almost 65% of the US population exhibits some degree of crowding.[1] Dental malalignment is either the result of an early loss of space in the early or mixed dentition, a slippage of contacts, or a combination of the two. The most common ways to quantify malalignment are a tooth size arch length discrepancy (TSALD) and the incisor irregularity index (II).[11] TSALD and II are useful quantitative methods to describe dental malalignment both pre- and posttreatment. Posttreatment malalignment has long been a problem for orthodontists and will continue to be relevant until solutions are found. Many authors have investigated the issues of posttreatment crowding, identifying various factors. Despite their findings, long term stability is yet to be fully understood. Few authors have examined the role that arch form or shape plays in stability. More specifically, little research exists on the relationship between the arch form's overall shape and posttreatment stability.

A narrow arch form comprised of acute contact angles may have an increased risk of slippage of dental contact points leading to untreated malalignment and posttreatment relapse.

This literature review will first discuss dental malalignment and the most commonly used methods for quantifying malalignment. Following, the prevalence and etiology of dental malalignment and post treatment relapse will be highlighted to emphasize the importance of understanding new treatment modalities. Finally, arch form and its various classifications will be examined before leading into the objectives and methodology of the current study.

2.1. Methods to Measure Dental Malalignment

There are two common ways to measure dental malalignment, TSALD and II. A tooth-size-arch-length-discrepancy (TSALD) exists when the summation of the tooth widths, measured from the mesial to distal anatomical contact points, exceeds the amount of space available in the arch. TSALD can be divided into anterior and total measurements. Anterior TSALD measures arch perimeter from canine to canine, and total TSALD measures arch perimeter from molar to molar. In early TSALD analyses, the total space available in the dental arch was measured utilizing a brass wire along an "outside" perimeter. In 1947, Nance[15] described this adaptation of a brass wire to the middle third of the buccal surfaces of the mandibular teeth on a plaster model. When straightened, the wire could be measured to provide the total arch length available. The final discrepancy could then be calculated by subtracting the sum of mesial-distal widths of all teeth from the total arch length. After the publications of Tweed[32], orthodontists began to position the dentition over the underlying denture base in which it is housed. Following this philosophy, Huckaba[33] modified the arch perimeter wherein a 0.025" brass wire was subjectively positioned along the mandibular arch to measure the underlying basal bone housing. Over the posterior dentition, the wire was centered on the interproximal contacts. Over the anterior dentition, the position of the wire was determined by the labial lingual positions of the incisors. If the teeth were positioned upright over basal bone, the wire was centered along the incisal edge. If teeth were displaced labially, the wire was positioned lingually to account for uprighting of the incisors. If teeth were lingually displaced, the wire was positioned more labially to account for incisor proclination.

A simpler method, recommended by Proffit et al.[34], calculates arch perimeter by separating the dental arch into quadrants. In the posterior quadrants, linear measurements are made from the mesial of the first permanent molars to the mesial of the ipsilateral canines. In the anterior quadrants, linear measurements are made from the mesial of the canines to the mesial of the ipsilateral central incisors. A TSALD exists when the sum of the mesial distal widths of the teeth in a quadrant exceeds the linear measurement of that quadrant. Variations in what constitutes a quadrant exist in the literature, as described by Bishara et al.,[5] but either application is appropriate.

In 1975, Little[11] developed an alternative method for measuring dental malalignment. His method, the incisor irregularity index (II), measures the horizontal linear displacement of adjacent anatomic contact points of the mandibular incisors. The total sum, obtained in millimeters, of the five displacements represents the degree of incisor irregularity. Thus, lower incisors in ideal alignment would receive a score of 0-0.9. Minimal malalignment can be anywhere from 1 to 3, while moderate malalignment can be anywhere from 4-6. Severe malalignment can be 7 to as high as 10 or above in extremely malaligned cases. Although claiming its effectiveness and simplicity, Little admitted to the limitations of his method. In cases with mandibular incisor spacing, the incisor irregularity should only measure labiolingual displacements. The mesiodistal linear measurements seen in spacing are ignored. Little claimed the inclusion of spacing as a negative value would distort the meaning of the irregularity index, a method developed to represent crowding alone. Furthermore, the II ignores the position of the incisors to the ideal arch. A mandibular arch with an II score of 0 could still possess a discrepancy with the TSALD method described by Huckaba.[33] Most importantly, the II tends to exaggerate malalignment in certain cases with little anterior TSALD. Due to the similar labiolingual and mesiodistal dimensions of lower incisors, as described by Peck and Peck,[35] severely rotated incisors can give a high II when arch perimeter is maintained. Harris et al[12] expounds on this scenario with an example case of a 13.5 year-old boy with an II of 14.1 mm but a TSALD of 1.9 mm. Because of the differences between TSALD and II, it is no surprise the variation in II only explains 28-36% of the variation in TSALD, and vice versa.[10, 12] In the summary of his publication, Little reiterates, "The Index is not an arch length assessment but, rather, a guide to quantifying mandibular anterior crowding." Both II and TSLAD are useful tools to quantitatively describe dental malocclusion. Although different, they complement each other in helping the clinician diagnose crowding in the lower anterior dentition.

2.2. Prevalence of Dental Malalignment

In 1900, Edward Angle[36] coined the term malocclusion to describe teeth that were not correctly positioned in the line of occlusion. He classified malocclusions according to the relationship between the maxillary and mandibular first molars. Class I, or neutrocclusion, exists when the mesiobuccal cusp of the maxillary first molar aligns with the buccal groove of the mandibular first molar. Class I malocclusions exhibit a wide array of malaligned teeth, including rotations, spacing, deep bits, open bites, and cross bites. Most often, Class I malocclusions involve the malposition of the anterior teeth. This phenomenon has become so common that there are now more people that have Class I malocclusions than those that have normal occlusion. In 1965, Cryer[37] found the incidence of mandibular incisor crowding to be 62% among 1000 schoolchildren aged 14 years old. Proffit et al.[1] gathered data from the third National Health and Nutrition Examination Survey (NHANES III) and found that 65% of all racial and ethnic groups in the United States possess some form of incisor irregularity. Applying the Index of Treatment Need, they determined 57 to 59% of all racial and ethnic groups need orthodontic treatment. In the maxilla, malocclusions ranged from ideal (II: 0-1 mm) for 44% of the US population, mild-to-moderate (II: 2-6 mm) for 45%, and severe (II: >6 mm) for 11%. In the mandible, malocclusions were ideal for 37%, mild-to-moderate for 49%, and severe for 14% of the US population.[1] Buschang and Shulman[2] found that among untreated individuals from 15 to 50 years of age, about 40% had incisor irregularities that were considered clinically significant. Clinical significance was established as an incisor irregularity equal to or great than 4 mm. Applying this measure to the data published by Proffit et al.,[1] 30-40% of their sample had incisor irregularities that were clinically significant.

Left untreated, Class I malocclusions tend to worsen over time. Little and Sinclair[3] examined the casts of 65 untreated individuals from mixed dentition (9 to 10 years old) to adulthood (19 to 20 years old). They found a net increase in II, and this increase was similar to posttreatment changes in a similar sample. Bishara et al.[4, 5] examined even longer-term data from patients in the Iowa Growth Study and found an increase of 2.4 mm in anterior TSALD between 14 and 25 years of age and an additional 0.7 mm increase between 25 to 46 years of age. An even greater increase of 2.0 mm in anterior TSALD was found by Bondevik[6] for untreated adults between 23 to 34 years of age. Richardson[7] found very similar results to Bishara, reporting a 2.3 mm increase in total TSALD between 13 and 18 years of age.

The location of dental malalignment is important to examine because it may provide insight about the mechanisms by which malalignment occurs. Data from the NHANES III survey reveals that crowding most often occurs between the canine and lateral incisor for both maxillary and mandibular arches.[9, 29] The least likely contact in either dental arch to have a discrepancy is between the two central incisors. This discrepancy pattern being greatest between the canine and lateral incisor was consistent for any degree of malalignment, whether mild or severe. Furthermore, the pattern was evident in both treated and untreated individuals.[9, 29]

Dental malalignment consistently coincides with decreases in arch perimeter, length, depth, and width. Little and Sinclair[3] noted a 2 mm decrease in arch length in conjunction with a 0.7 mm increase in II. Bishara et al.[4, 5] discovered an inverse relationship between the two factors, with greater amounts of crowding associated with greater decreases in arch length. This correlation is simply a result of teeth moving mesially in the arch as crowding worsens. Mesialization of teeth has been recognized as a natural compensatory mechanism. When deciduous molars are lost prematurely, posterior teeth will drift mesially.[17] If interproximal contacts are compromised by removing tooth structure between adjacent teeth, mesialization will occur to reapproximate adjacent teeth.[13] However, when space is not available in the arch, teeth move mesially as a result of slippage of contacts and crowding ensues.

2.3. Myths Surrounding Dental Malalignment

Before discussing the etiologies of dental crowding, it is important to review the false notions pertaining to malocclusions. Becoming familiar with these myths will prevent misinterpretations and help to avoid unwarranted treatment. Perhaps the most common of these is the idea that third molars contribute to mandibular crowding. Harradine et al.[38] performed a randomized clinical trial on 164 patients who had just completed treatment. They randomly assigned early third molar extractions and found no evidence to justify the removal of third molars to prevent incisor crowding. Previous studies supported this same notion.[39, 40] Furthermore, individuals with both mandibular third molars had, on average, 1 mm less II than individuals with either one or both third molars missing.[2] In reality, this myth is merely a coincidental event. Third molars, on average, erupt at 19-20 years of age.[34, 41] This falls within the age range where mandibular TSALD increases anywhere from 1.1 mm to 2.4 mm.[5, 23]

Peck and Peck[35] investigated tooth morphology as a causative factor. They compared a group of individuals with naturally well-aligned teeth against a control group. Their findings suggested that well-aligned teeth were smaller mesiodistally and larger faciolingually, while the opposite was true for malaligned teeth. However, more recent, well designed studies have not been able to recreate their findings, disproving the notion that certain tooth morphologies are more likely to result in dental malalignment.[42-45]

The size of the underlying apical base has been investigated as a factor in predicting Class I malocclusions. It was thought that a larger apical base would allow for more room for the dentition and reduce the likelihood of malpositions. No relationship has been found between the size of the mandibular apical base and mandibular crowding.[46]

It is also a myth that pre-treatment crowding is related or can be used to predict postretention crowding. To date, no statistically significant association between greater pre-treatment discrepancies and postretention discrepancies has been identified. Furthermore, there is not a decreased likelihood for posttreatment crowding for individuals requiring extractions. In fact, Myser[10] found the opposite to be true, with greater postretention malalignment seen in extraction than nonextraction cases.

Most importantly, there is no evidence that well-performed orthodontic treatment reduces the incidence of late incisor crowding. Even when incisors are upright over basal bone, when intercanine width is maintained, and when appropriate retention is implemented, individuals are still at risk for postretention malalignment. In fact, this malalignment is clinically similar for individuals treated with extractions (2.2 mm II increase), without extractions (1.9 mm II increase), or not treated at all (2.2-2.3 mm II increase).[4-7, 9] Thus, there must be other mechanisms responsible for dental malalignment.

2.4. What Dental Malalignment Is Related To

The etiology of dental malalignment can be divided into early (prior to permanent dentition) and late (permanent dentition) stages. Early crowding at its fundamental root is due to a loss of arch space. On the other hand, late crowding is more closely related to the slippage of contacts. In both events, teeth move mesially in the arch, reducing arch perimeter and increasing TSALD.

For early crowding, the transseptal fibers are responsible for much of the space loss that occurs. These fibers connect adjacent teeth and nearby teeth. These linkages represent a natural mechanism to maintain interproximal contacts.[14] As stated earlier, when interproximal contacts are compromised and space is created between them, transseptal fibers will pull teeth mesially to regain contact.[13]

One way space is lost in the dental arch is through early exfoliation of primary teeth, which are larger than their permanent successors. This discrepancy in size is known as leeway space. Nance[15] first described this gain in arch space, noting that there was an average of 1.7 mm of space created on each side of the mandibular arch. Moyers et al.[16] found the gain in space to be larger, gaining 2.5 mm per side in the mandible and 1.5 mm per side in the maxilla. The larger primary teeth that account for leeway space are nature's best space maintainers. If any of these teeth are lost to caries or premature exfoliation, the risk of crowding greatly increases. As soon as the space is created, posterior teeth move mesially in the arch and consume arch length. This mesial migration can be up to 4-5 mm when both primary molars are lost, resulting in an increased TSALD when transitioning to the permanent dentition.[17]

Early space loss leading to crowding is also affected by disruptions in the eruption sequence of teeth. When an abnormal pattern of exfoliation and eruption takes place, there can be a higher incidence of crowding. Lo[18] investigated various sequences of eruption in schoolchildren, finding that crowding was greater in individuals whose second molars erupted prior to their canines and premolars. In the mandible, it was also greater when premolars erupted before the canine erupted. It seems the natural sequence of exfoliation is in place to preserve leeway space, and its most favorable pattern is from anterior to posterior. Abnormal eruption also occurs when permanent teeth fail to emerge and remain impacted in the basal bone, as commonly seen with impacted canines.[19-21] Some impactions are a consequence of early loss of primary teeth which leads to posterior teeth moving mesially in the arch. As stated earlier, this results in a decreased arch perimeter, providing no room for the impacted tooth to emerge. Other cases of impaction result from a permanent tooth failing to erupt. When the corresponding primary tooth can no longer hold arch space and exfoliates due to natural causes, posterior teeth will move mesially into the space. In either scenario, a loss of arch space occurs, and dental malalignment is inevitable.

Late dental crowding, which occurs in the permanent teeth, is of primary importance to this study. All late dental crowding is affected by the displacement of tooth-to-tooth contacts, leading to the malalignment of teeth. One of the primary ways contacts become displaced in growing individuals is during the vertical eruption of teeth. Little[47] compared II in two groups of Class I extraction patients: stable and unstable. The unstable group, who had an II greater than 2 mm, was found to have significantly more eruption of the mandibular incisors. Long term follow-up data by Driscoll-Gilliland[23] confirmed these findings, correlating mandibular incisor crowding to vertical growth in both treated and untreated individuals. As teeth erupt vertically, there is a greater chance for adjacent tooth contacts to become displaced.[48] Vertical craniofacial growth continues into an individual's 2nd decade of life, emphasizing the potential for dental malalignment after adolescence.[25, 49]

Teeth can also slip contacts when anteriorly directed forces are applied. Due to the biomechanics involved in the musculoskeletal pattern of the jaws and the inclinations of the dentition, occlusal bite forces exert a substantial vector of anterior force. This was first measured by Southard et al.[26] in 1989, who found that the force progressed anteriorly through the dentition from second molar to central incisor. In some individuals, this anterior force created during occlusal loading extended past the midline. After this discovery, Southard et al.[27] investigated the relationship between this anterior component of occlusal force and dental malalignment. A positive relationship was found between the magnitude of anterior force and dental crowding. Furthermore, dental crowding was related to tighter posterior contacts. Tighter contacts were shown to have less sequential force decay, resulting in more anterior force available to jeopardize tooth contacts.

Dental restorations can also produce excessively tight interproximal contacts. When an oversized restoration is placed between two teeth, an anterior component of force is created to achieve a “tight” contact. Furthermore, subsequent occlusal bite forces are increasingly likely to be distributed anteriorly to the incisors as a result. These factors could be responsible for a slippage of contacts in patients who receive interproximal restorations after orthodontic treatment. Incisor irregularity and TSALD was significantly more (0.9 mm and 0.4 mm, respectively) in patients with interproximal restorations than patients without.[10]

The common denominator of the above etiologies is contact slippage. As noted previously, the most likely location for a contact to slip is between the canine and lateral incisor. This contact is located at the greatest curvature of the arch, where the posterior segment transitions to the anterior segment. The degree of this curvature can vary depending on the shape of the anterior arch form. A narrow, tapered anterior arch form has a sharper turn at this susceptible location. A broader anterior arch form, on the other hand, rounds more gradually around the greatest curvature. In fact, individuals with narrow mandibular arch forms have been shown to have more posttreatment crowding than individuals with broad arch forms. Mills[50] studied malalignment in 230 males with neutrocclusion between the ages of 17 and 21. A positive association was found between dental malalignment and decreasing arch width, measured at canine, 1st premolar, and 2nd premolar. On average, the arch width between 2nd premolars was 4 mm narrower in individuals with malalignment than those with good alignment. McKeown[51] collected 65 dental casts of individuals from 18 to 25 years of age. He found a significant positive correlation between malalignment and decreasing arch width, emphasizing that a narrow arch predisposes one to dental malalignment. Myser[10] evaluated postretention malalignment in 66 patients treated by 7 experienced orthodontists. Significant correlations were found between postretention II, decreasing intercanine width, and decreasing anterior arch perimeter. The posttreatment interdental angle, measured as the angle formed by lines through the mesial and distal contact points of contralateral teeth, for mandibular lateral incisors was significantly related to incisor irregularity, with a greater angle corresponding to lesser incisor irregularity. Furthermore, the posttreatment interdental angle between canines was significantly related to TSALD, with greater angles corresponding to lesser TSALD. These findings suggest that a broader arch form may be related to decreased posttreatment malalignment. This broader arch shape may also explain why nonextraction patients had less posttreatment malalignment than extraction patients, averaging 0.8 mm less II and 0.5 mm less TSALD.[10] It may be that individuals with extractions have narrower arch forms and, thus, a greater likelihood for contact slippage between the smaller contact angles of the canine and lateral incisor. This contact angle was, on average, 10 to 15 degrees more acute than any other contact angle in the anterior arch.[10] To further investigate this relationship, arch forms will be reviewed, including methods of classification and historical arch shapes.

2.5. The Methods of Classifying Dental Arch Forms

Perhaps the simplest way to classify dental arch forms is through the use of nominal variables. Chuck[52] categorized arch forms into tapered, ovoid, and square.

These descriptors were purely qualitative in nature. Tapered arch forms had the narrowest intercanine width. Square arch forms had the widest width, and ovoid arch forms fell in between. Although useful to a clinician, these variables are lacking in what was needed for dental and orthodontic research. Quantitative measurements became a useful tool in comparing dental arches. Arch widths can not only be measured from canine to canine, but between premolars and molars as well. Arch depth is another measurement used to quantifiably compare dental arches. There is no consensus in the literature as to the definition of arch depth. For the purposes of this study, arch depth will be defined as the anteroposterior measurement lying perpendicular to arch widths along the midline of the dental arch. This measurement spans from incisal edge of the central incisor to a posterior delineation, usually the mesial contact of the first molar. Although many studies look at the long-term changes that occur independently in these arch form measurements, [2, 4, 5, 53] the concerns of this study are focused more on the ratio between arch depth and width. Arch forms with a greater relative arch depth than width are classified as tapered or narrow. Arch forms with a lesser relative arch depth than width are classified as broad.

Other simple quantitative measurements to analyze arch forms were described by Myser.[10] The first one, contact angle, is a measure of the angle formed by two adjacent teeth when lines are drawn through their mesial and distal anatomic contact points. This angle can be a useful predictor of which contacts may slip and result in crowding. The other measurement, interdental angle, records the degree of obtuseness between contralateral teeth when lines are drawn through their mesial and distal anatomic contact points. Although not a descriptor of the entire arch, these measurements can help pinpoint where contact slippage may occur, helping clinicians better retain their cases.

Before discussing more complex methods to classify arch form, a review of historical arch forms will be introduced to better understand the mathematical evolution that occurred in finding the best way to describe arch form.

2.5.1. Historical Arch Forms

As orthodontic research progressed through the late 19th and early 20th century, more studies began developing geometric and mathematical models to create the ideal arch form. Perhaps the first person to develop a set of ideals was Bonwill.[54] In studying the human anatomy, Bonwill declared the lower jaw should form an equilateral triangle with the base extending between condyles, and the sides extending anteriorly from each condyle to a median line at the incisors. Lining up along the sides of this triangle should be the molars and premolars, and each side should never vary ¼ inch beyond the average length of 4 inches. Bonwill emphasized that anatomy is in "perfect consonance with geometry, physics, and mechanics…If nature is given a fair chance to right herself, she will return to the normal standard of mathematical and mechanical precision; to do otherwise would annihilate creation."

In 1904, Hawley[55] modified the postulates of Bonwill. He proposed replacing the apex of the equilateral triangle with a circle whose radius equaled the combined widths of the six anterior teeth. The anterior teeth would lie along the circle, while the posterior teeth fell along a line extending from the distal of the canine to the condyle. Calling bluff on Bonwill's promise of annihilation, however, Hawley advised against the religious use of his method for determining arch form. He suggested it merely be a guide, rather than a formula. More than a century later, Hawley's advice should still be heeded, as arch forms are being determined by orthodontinc manufacturer companies.

2.5.2. Mathematical Applications to Arch Form

In the century following, many authors attempted to describe the ideal arch form. Although not all of them were exactly similar, these arch forms could be generalized into one of three different symmetrical shapes. The first of these shapes used to describe the dental arch form is a parabola. In its most general sense, a parabola is a symmetric, U-shaped curve. The exact definition is the curve formed when a plane intersects a cone while oriented parallel to the cone's side. The most widely recognized application of parabolas in nature is to describe flight path of a projectile under the influence of gravity, mathematically described as $y = x^2$. Adapting this formula to a more accurate representation of arch form, various authors gravitated towards a parabola of the general form $x^2 = 2py$. These authors included Mills and Hamilton,[56] Biggerstaff, [57] Hechter,[58] and Currier.[59]

Other authors, including Scott,[60] Burdi,[61] Burdi and Lillie,[62] MacConaill and Scher,[63] and Pepe, [64] proposed a catenary curve to describe dental arch form. Historically, a catenary is the curve a chain will take when hung under its own weight while supported on either end. Mathematically, the curve can be calculated as $y = (e^x + e^{-x})/2$. Many arch forms today, including Roth, are based on a catenary arch.

Ellipses were yet another shape being applied to describe ideal arch forms. Biggerstaff,[57] Currier,[59] and Izard[65] all investigated an ellipse of the general form $\left(\frac{x^2}{b^2}\right) + \left(\frac{y^2}{a^2}\right) = 1$. Currier[59] compared ellipses and parabolas to find which curve best fit the various aspects of an ideal dental arch. He found that ellipses provided a better goodness of fit along an "outer curve" which followed the buccal cusps and incisal edges of teeth. Parabolas, on the other hand, were found to provide a better goodness of fit along a "middle curve" through the central fossa of posterior teeth and cinguli of anterior teeth. Given the majority of orthodontics is practiced along the "outer curve", with brackets bonded facially to teeth, Currier determined an ellipse to be the better guide for arch form.

In 1972, Brader[66] expounded on the elliptical arch form, proposing a new ideal arch strong enough to withstand the "counterbalancing force fields of the tongue and of the circumoral tissues." His arch form was based on a trifocal ellipse, shaped much like an egg. Despite earning him the 1971 Milo Hellman Research Award, Brader's work with trifocal ellipses and the theoretical *PR=C* force system has been outdated by newer technology. These new models utilize mathematical curve fitting to uniquely and quantitatively classify a dental arch form.

Despite Bonwill's claims, an individual's natural dentition never perfectly follows a geometric curve. One inherent flaw with the above models is they are all perfectly symmetric, unlike the natural dentition.

Hechter[58] first touched on the asymmetry of dental arch forms. He found natural asymmetry existing in normal occlusions, and orthodontic correction of this asymmetry was not always stable. BeGole[67] utilized the cubic spline function to mathematically describe arch form while addressing inherent asymmetries. This method of curve fitting, which uses custom placed "knots," gives the clinician utmost flexibility to accurately model an individual arch form. However, this customized advantage developed by BeGole also prevents arch forms from being quantitatively compared to one another. Due to these complications, symmetrical curve fitting will be utilized in the present study to compare arch forms with posttreatment crowding.

In 2008, AlHarbi et al.[30] published a comprehensive mathematical analyses of dental arch form configurations. They digitized 40 casts of normal occlusion and curve fitting was performed using the following mathematical functions: beta function, polynomial equations, natural cubic splines, and Hermite cubic splines. Each of these methods are described below. Conic sections (i.e. circles, ellipses, parabolas, and hyperbolas) were not tested in this study due to their inherent limitations in curving fitting to individual arches.

Beta function, as described by Braun et al.[68], requires two measurements to generate the dental arch shape, molar width and arch depth. Molar width, denoted W, is measured at the distobuccal cusp of the second molar. Arch depth, denoted D, is the average perpendicular distance from the central incisors to the molar cross-arch dimension.

The beta function expressing dental arch shape is represented by the formula:

$$y = 3.0314D\left(\frac{x}{W} + \frac{1}{2}\right)^{0.8}\left(\frac{1}{2} - \frac{x}{W}\right)^{0.8}$$

The major limitation of beta function is that it bases the entire dental arch shape on two parameters. Although Braun reported a high correlation between the formulated arch shape data and true arch width and depth, there is no correlation accounting for the rest of the arch shape. The lack in amount of arch curve being fit is best exemplified by an infinite number of dental arch shapes possible for a given arch width and depth. Despite the countless arch shapes that have the same arch width and depth, beta function would formulate one curve to match them all.

Natural cubic splines are curves composed of consecutive, individual third-order polynomials, denoted by the formula:

$$y = a_3x^3 + a_2x^2 + a_1x + a_0$$

Each individual polynomial is bound by two points, called knots. During curve fitting, these knots are subjectively placed to most accurately represent the arch shape. AlHarbi[30] tested both 5 and 7 knot cubic splines, placing points from second molar to second molar. They also tested Hermite cubic splines, which are similar to natural cubic splines but are comprised of individual curves denoted by a blend of four formulas:

$$y_1 = 2x^3 - 3x^2 + 1$$

$$y_2 = -2x^3 + 3x^2$$

$$y_3 = x^3 - 2x^2 + x$$

$$y_4 = x^3 - x^2$$

Although theoretically more customizable, both types of cubic splines were shown to behave quite erratically between knots. Natural cubic splines could be improved by increasing the number of knots, as the curve is forced to pass through each knot. However, as the number of knots increases, so too does the irregularity of the polynomial segments. Hermite cubic splines, on the other hand, were more flexible and smoother throughout the designated knots, giving them an advantage in fitting irregular dental arches.

Polynomial equations are generally represented by the formula:

$$y = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_2 x^2 + a_1 x + a_0$$

where the a_i (a_0, a_1, a_2, . . . , a_{n-1}, a_n) are polynomial coefficients and *n* is the order or degree of the polynomial. Odd-numbered coefficients a_1 and a_3 are representative of left and right symmetry. Even-numbered coefficients a_2 and a_4 are representative of arch taperedness and squareness, respectively.

The results of the analyses showed that fourth-order polynomial functions best fit the arch form when compared to beta functions, natural cubic splines, and Hermite cubic splines. Furthermore, fourth-order polynomials were superior in fit against second- to twelfth-degree polynomials. Pepe[64] argued that sixth-order polynomials better fit dental arch forms. However, she only tested polynomials on 7 subjects, all of whom had normal occlusion. Sixth-order polynomials, when fit to irregular arch forms, too closely approximate irregularities. In doing so, they create a dental arch form that is unnatural and lacking in smooth curvature. While Hermite cubic splines most closely follow dental arch form irregularities, the natural curvature produced by fourth-order polynomials makes it the ideal candidate for evaluating arch form in posttreatment malaligned cases.

The purpose of the present study is to investigate the possible relationship between arch form or shape and posttreatment malalignment. Dental casts of 50 extraction and 50 nonextraction patients, controlled for age and sex, were collected at both posttreatment (T2) and postretention (T3). Casts were digitized with Dolphin, capturing the following fourteen points: midincisal points of incisors (to minimize effects of rotations), canine cusp tip, buccal cusp tip of the premolars, and the mesiobuccal and distobuccal cusp tips of the first molars. Fourth-order polynomials were constructed to best fit the dental arch form and used to detect correlations between arch form and posttreatment malalignment.

3. MATERIALS AND METHODS

3.1. Sample

The study pertains to 100 previously treated orthodontic patients, including 51 (40 female, 11 male) extraction and 49 (42 female, 7 male) nonextraction cases. There was no statistically significant difference in the proportion of males and females in each treatment group (p=0.343). The subjects were evaluated based on treatment modality at posttreatment (T2) and postretention (T3). While there was no difference in the T2 age between treatment groups, the extraction group was significantly older at T3 (Table 1).

All patients were treated by three private practice orthodontists at their respective practices: Drs. Alexander (Arlington, TX), Vaden (Cookeville, TN), and Boley (Richardson, TX). To be included in the study, cases had to have been finished with good occlusions (i.e. clinical Cl I canine relationship and acceptable overjet, overbite, alignment, and interocclusal contact) and had to have been treated with conservative, traditional orthodontic treatment (i.e., no excessive flaring of incisors, no excessive increase in canine width, maintaining teeth over basal bone). To be included, the posttreatment and postretention models also had to be of acceptable quality. Postretention records must have been taken a minimum of 5 years posttreatment and 3 years postretention. Exclusion criteria included craniofacial anomalies, orthognathic surgery, previous orthodontic treatment, and restored missing teeth. This project was approved by the Texas A&M University IRB 2018-1473-CD-EXM.

3.2. Measurements and Procedures

Posttreatment (T2) and postretention (T3) maxillary and mandibular models of the extraction cases were scanned using the Ortho Insight 3D Scanner (Motion View, Chattanooga, TN); the nonextraction cases were scanned using the Lythos Intraoral Scanner (Ormco, Brea, California). The digital scans were exported as .STL files and uploaded into Dolphin Imaging Software (Chatsworth, CA). Digital models were oriented with the midline along the maxillary midpalatal suture and the occlusal plane along the functional occlusal plane.

Various predictor variables were measured at T2 on both the maxillary and mandibular models, including contact angles and arch dimensions. Contact angles between canine-lateral and lateral-central were measured according to Myser et al.[10] as the intersecting angle between lines drawn through the mesial and distal contact points of adjacent teeth (Figure 1). Replicate analyses of 20 sets of models produced method errors for contact angles that ranged from 2.1-5.4˚.

Arch dimensions were measured parallel to the occlusal plane, including canine and molar arch depths, canine width, and molar width. Canine arch depths were measured on a horizontal plane extending perpendicular from the most lingual margin of each canine to the contact point between the central incisors (Figure 2). Molar arch depths were measured on a horizontal plane extending perpendicular from the mesial aspect of the permanent first molars to the contact point between the central incisors (Figure 3). Canine widths were measured at the most lingual margin from canine to canine (Figure 4). Molar widths were measured at the junction of the lingual groove and gingival margin from molar to molar (Figure 5). Ratios of arch widths to depths were then calculated for canine width/depth and molar width/depth in the maxilla and mandible. Replicate analyses of 20 sets of models produced method errors for arch dimensions that ranged from 0.17-0.32 mm.

To describe arch shape independent of the AP position of teeth, the maxillary and mandibular posttreatment (T2) models were digitized (14 points for the nonextraction arches and 12 points for extraction arches) using the 3D tool in Dolphin Software (Figure 6). These points were adapted from the protocol described by AlHarbi et al.[30]

The digitized points were exported from Dolphin as rectangular (X,Y) coordinates and uploaded to Microsoft Excel. Arch shape was quantified from the coordinates using a fourth-order polynomial, which has been shown to provide the best fit for dental arches.[30] The fourth-order polynomials were estimated using the following formula:

$$y = a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0$$

where x represents arch width, a_0 through a_4 represent polynomial coefficients, and y represents arch depth. The polynomial constant, a_0, represents the intercept of the y-axis and corresponds to the contact point between the central incisors.

Variability in arch shape was investigated by extrapolating five arch depths from each of the polynomials. The polynomial constant, a_0, was controlled for by setting its value to 0, equivocating the midincisal point for shorter extraction arches and longer nonextraction arches. Arch depths (y) were calculated from the polynomial functions at width (x) values of +10, +15, +20, +25, and +30 mm. Individual arch shapes were plotted along the x-axis from -30 to +30mm, mirroring the calculated depths across the y-axis. Variability in maxillary and mandibular computed arch shapes were displayed graphically for sex and treatment. Mean arch depths were calculated for sex and treatment groups to compare computed maxillary and mandibular arch shapes~~.~~ Generating arch shapes from the polynomials allowed for comparisons independent of arch size.

TSALD and II were recorded at posttreatment (T2) and postretention (T3). Tooth-size-arch-length-discrepancy was calculated for the total arch perimeter (from mesial of first molar to mesial of first molar) using the fourth-order polynomial curve best fit as a guide for total arch perimeter. Tooth sizes were measured from digital models using Dolphin's 3D tool. Incisor irregularity was calculated according to Little.[11] Changes in TSALD and II, denoted TSALDΔ and IIΔ, respectively, were calculated by subtracting T2 values from T3 values. Replicate analyses of 20 sets of models produced method errors for malalignment measurements that ranged from 0.24-0.67 mm.

3.3. Statistical Analyses

All of the data were imported in SPSS Version 25 (IBM SPSS Statistics Inc., Armonk, NY) for statistical testing. The significance level was set at 0.05. The skewness and kurtosis statistics indicated all of the continuous variables were normally distributed. Bivariate Pearson product moment correlations were performed for all variables. Independent sample t-tests were used to evaluate sex (M, F) and treatment (extraction, nonextration) differences. Based on the assumption that the arch shapes estimated by the polynomials were related, principle component factor analyses with varimax rotation were performed to reduce the number of variables and produce multivariate composite variables for each subject.

4. RESULTS

Malalignment increased significantly ($p<0.006$) from T2 to T3 in all groups excluding two. Maxillary TSALD did not increase significantly from T2 to T3 in males (0.15 mm, $p=0.366$) and in nonextraction cases (0.12 mm, $p=0.219$). TSALD and incisor irregularity showed no statistically significant sex differences at T2, T3, or for the changes that occurred from T2 to T3 (Table 2). When comparing extraction to nonextraction, only maxillary TSALD at T3 was statistically significant, with extraction arches exhibiting more crowding than nonextraction arches, but it was not statistically significant after Bonferroni corrections (Table 3).

Maxillary TSALD changes were moderately correlated to maxillary II changes (Table 4). Mandibular TSALD changes showed an even stronger correlation with mandibular II changes. While maxillary TSALD changes appeared to be related with mandibular TSALD changes and mandibular II changes, the associations were not statistically significant after Bonferroni corrections.

The contact angle between mandibular canines and lateral incisors was the smallest, followed by the contact angle between maxillary canines and lateral incisors (Figure 7). There were no statistically significant differences between males and females for any contact angles (Table 5). Treatment modality showed that the maxillary and mandibular canine to lateral incisor contact angles were significantly smaller in extraction cases than in nonextraction cases (Table 6). After Bonferroni corrections, only the mandibular differences were statistically significant, with the mandibular canine to lateral incisor contact angles 6 to 10 degrees smaller in extraction cases.

All but one of the dimensions (i.e. maxillary molar depth) were smaller in females than males. The majority of arch dimensions showed no significant sex differences (Table 7). Canine width was significantly wider for males in both the maxilla and mandible. After Bonferroni correction, only mandibular canine depth was significantly different, with males having slightly deeper canines than females. Most of the arch dimensions showed statistically significant treatment group differences (Table 8). Extraction arches had significantly shorter molar depths and widths. Mandibular canine widths were significantly larger in extraction cases, as were maxillary canine depths.

Dental arch shape, represented by the ratio of arch width to arch depth, showed no statistically significant differences between males and females (Table 9). Extraction cases were relatively wider at the molar depth in both the maxilla and mandible (Table 10).

The factor analyses produced two factors for the maxilla and two factors for the mandible (Table 11). Factor 1 was a posterior arch factor, with primary contributors from arch depths calculated at widths of +25 mm and +30 mm. Factor 2 was an anterior arch factor, with primary contributors from arch depths calculated at widths of +10 mm and +15 mm. In the maxilla, factor 1 explained 71.02% of the variance, factor 2 explained 28.33% of the variacne, and together they explained 99.35% of the total variance. In the mandible, factor 1 explained 63.04% of the variance, factor 2 explained 36.30% of the variance, and together they explained 99.34% of the total variance.

When comparing sex differences, the posterior arch was broader in males (Table 12). This difference was statistically significant in the posterior mandible (Figure 8). The two treatment groups also differed in the shape of the posterior arch (Figure 9). Nonextraction arches were significantly broader in the posterior mandible (Table 13). Broader posterior maxillary and mandibular arches were significantly correlated with smaller changes in maxillary TSALD (Table 14).

Individual arch shapes showed a great degree of variability among the sex and treatment groups (Figures 10 -17). At an arch depth of 30 mm, variability in arch width ranged from 40 mm to almost 60 mm.

5. DISCUSSION

Posttreatment arches are broader in males than female. The present results showed that after controlling for arch size, the posterior arches of males were 5-10% broader. It has been previously demonstrated that males have broader arches. Kageyama et al.,[31] who used fourth-order polynomials to describe arch shapes, showed that, among various facial types, males had broader arches than females. These sex differences in arch shape may be attributed to males having larger jaws. Apical bases analyzed from CBCT have shown significant sex differences, with males having broader maxillary and mandibular apical bases. While apical base measurements do not directly refelct dental arch shape, the two have been shown to be significantly related.[46] Larger jaws were also demonstrated by Newman et al,[69] who found males to have wider mandibular apical bases than females.[69] Furthermore, these sex differences in mandibular width increased over time.

Sex differences in arch shape could be related to muscle strength. Males have been consistently shown to have significantly stronger maximum bite forces than females, indicating stronger masticatory musculature.[70-73] Moreover, the force of orofacial musculature has been related to vertical growth patterns, with stronger musculature associated with hypodivergent patterns.[73, 74] This is of importance because hypodivergent patients have broader arch shapes.[75, 76] Sex differences in posttreatment arch shape may help explain the smaller increase in posttreatment malalignment previously reported for males.[3, 5, 22, 25, 77, 78]

In contrast, the current study found no sex differences in dental arch dimensions. Previous studies have shown that males have significantly larger dental arch dimensions. Howe et al.[79] measured linear dental arch dimensions and found that males had significantly greater maxillary and mandibular arch dimensions than females. Bishara et al[4] showed that all arch dimensions were greater in untreated males, except for mandibular canine width. The lack of significant differences in the present study may be due to the small number of males (18%) and relatively high number of extraction cases among the male sample. Males had a total of 11 extraction cases compared to only 7 nonextraction cases. This likely skewed the sample towards smaller arch dimensions because subjects with extractions have smaller arches.[80, 81] Sex differences in arch size could also be attributed to males having larger mesiodistal tooth dimensions.[82, 83]

When comparing dental arch form ratios, males did trend towards broader arch forms, with slightly greater ratios at the level of the maxillary canines and molars, and mandibular molars. The mandibular canine ratio was slighter greater for females, likely due to their decreased canine depth (F: 9.06 ± 0.83 mm, M: 9.68 ± 0.82 mm). Howe et al.[84] found that males have a greater maxillary and mandibular arch areas and perimeters, indicating a larger arch size. Bishara et al.[5] showed greater decreases in male arch lengths, including more uprighting of incisors, which would result in a broader arch shape.

Posttreatment mandibular arches of nonextraction patients are broader than arches of extraction patients. The patients treated nonextraction in the present study had arches that were 9-10% broader in the posterior region. No previous studies could be found to validate these treatment group differences. Isik et al.[85] compared pre- and posttreatment arch dimension changes of patients treated with and without extractions. They found that nonextraction arches increased in width compared to extraction arches, most notably in the premolar and molar regions. This may explain why the posttreatment nonextraction arches were broader in shape. Alternatively, it is possible that nonextraction patients actually have broader arches which could explain the differences in postretention malalignments previously reported.[8, 10]

In 1995, de la Cruz et al.[86] compared pre-and posttreatment arch shapes, described by ellipses, of patients treated with four premolar extractions. They found that not only did extraction arch dimensions decrease during treatment, but arch shapes became less narrow. However, this may have been due to the fact that pretreatment crowded arches, which are justifiably treated with extractions, are inherently more tapered than pretreatment uncrowded arches.[84] Also it is important to note that ellipses are inferior to the fourth-order polynomials used in the present study for quantifying arch shape.[30] Despite these changes towards a broader arch form, posttreatment extraction arches are still narrower than nonextraction arches. This was also reported by Myser et al.,[10] who described arch shape based on intercanine width, contact angles, and interdental angles. However, linear and angular measurements do not describe arch shape as well as fourth-order polynomials. Not only did their findings show narrower posttreatment arch shapes among extraction patients, but these narrower extraction arches displayed greater postretention malalignment. The most important difference between these findings and the current study is their less robust description of arch shape. Nonetheless, the differences in arch shape between treatment groups are important to note because Myser et al.[10] found greater postretention stability in nonextraction arches.

As expected, dental arch dimensions are significantly smaller in extraction than nonextraction cases. Molar depths were significantly less in extraction cases due to the absence of 2 premolars, which shortened total arch perimeter substantially. Molars were protracted anteriorly during space closure, moving them into a narrower portion of the arch. This explains why extraction arches had significantly smaller molar widths in both the maxilla and mandible. Canines, on the other hand, were brought posteriorly during space closure but into a wider portion of the arch. In the present study, canine widths were significantly larger in extraction cases for both the maxilla and mandible. Similar findings have been previously reported.[80, 81] Despite canines being retracted, mandibular canine depth was slightly less in extraction cases. Although not statistically significant, decreases mandibular canine depth might be attributed to mandibular incisor uprighting in extraction cases, bringing the contact point between the central incisors more posteriorly and reducing the overall arch depth.

Dental arch ratios were significantly greater in extraction cases at the maxillary and mandibular molars, as well as the mandibular canines. While these ratios suggest broader arch forms for extraction cases, their values are inflated due to significantly decreased arch depths resulting from extractions. Differences in arch dimensions between treatment groups is important because it emphasizes the importance of the current study's use of fourth-order polynomial derived arch shapes. By controlling for arch size, polynomial-derived arch shapes allow for an unbiased comparison of groups.

While there are no sex differences, contact angles are significantly smaller in extraction arches, with mandibular canine to lateral contacts being 6-10˚ smaller. Similarly, Myser et al.[10] found that mandibular canine to lateral contacts were 5-7˚ smaller in extraction than nonextraction arches. This contact angle was also the smallest of any site on the arch, indicating that the canine to lateral contact site is at the greatest risk for contact slippage. This notion is supported by the current study, which found that incisor irregularity was often greatest at the contact between canines and lateral incisors. While the present study did not evaluate postretention contact angles, Myser et al.[10] showed that contact angles decreased posttretention, indicating that tapered arch forms become more tapered.

Posttreatment posterior arch shape is correlated with posttreatment changes in maxillary TSALD, with broader posterior arches maintaining alignment to a greater degree than narrow arches. The present results showed that broader maxillary and mandibular arches are related to more stable arch changes. It has been previously shown that broader maxillary apical bases are correlated with less crowded maxillary and mandibular arches.[46] These associations are important because they suggest that broader posttreatment posterior arches, together with larger contact angles, lead to more stable orthodontic results. During normal occlusal loading, an anterior component of force is applied to the arch.[26] This anterior component of force has been shown to be correlated with dental malalignment.[27] The implication is that a broader arch, with larger contact angles, would more evenly dissipate this force along tooth contacts. Narrower arches, with smaller contact angles, are at a greater risk of contact slippage when an anterior component of force is applied along the arch.

There are moderate to strong correlations between posttreatment TSALD changes and incisor irregularity changes, both in the maxilla and mandible. The present results showed that maxillary TSALD accounted for almost 25% of the variability in maxillary incisor irregularity, and mandibular TSALD explained close to 60% of the variability in mandibular incisor irregularity. It has been previously shown that mandibular TSALD accounted for 28% to 36% of the variability in mandibular incisor irregularity.[10, 12] The higher correlations observed in the present study indicate that crowding (TSALD) and irregularity (II) may be more closely related than previously thought. However, much of the covariation of TSALD and II remains to be explained, reemphasizing the fact that they are measuring different attributes.

Overall, the treatment by these clinicians were very stable over the average 17.8 year posttreatment period. The average changes in maxillary and mandibular incisor irregularity from posttreatment to postretention were only 1.07 mm and 1.44 mm, respectively. At the long-term follow-up, only 15% of the sample had maxillary incisor irregularities greater than 3.5 mm, and only 16% of the sample had mandibular incisor irregularities greater than 3.5 mm, which is considered clinically insignificant.[87] These changes are less than the 1.63 mm change reported in a recent meta-analysis of 30 studies by Swidi et al.[8] Furthermore, the meta-analysis found a significantly greater change in incisor irregularity for extraction groups than nonextraction groups (ext = 1.74 mm, nonext = 1.40 mm).

This finding was consistent with the results for extraction cases in the present study. The extraction group also showed a greater increase in incisor irregularity than the nonextraction group, but the difference was not statistically significant (ext = 1.34 mm, nonext = 1.16 mm). Little et al.[87] evaluated cases treated with four first premolar extractions and found that the average mandibular II was 1.73 mm at posttreatment and 4.63 mm at postretention. Additionally, extraction cases evaluated by Myser et al.[10] had mean mandibular II of 1.52 mm posttreatment and 3.29 mm postretention. These extraction cases were not as stable as the extraction cases in the present study, which had mandibular II of 0.97 mm posttreatment and 2.54 mm postretention. These stable results may be the reason why no statistically significant differences were found between treatment groups.

In the present study, nonextraction arches showed fewer alignment changes than extraction arches, but the differences were not statistically significant. The change in mandibular incisor irregularity was 1.56 mm for extraction cases, and 1.30 mm for nonextraction cases. Myser et al.[10] found significant differences in malalignment changes between extraction and nonextraction cases. In their study, extraction cases exhibited greater increases in mandibular irregularity (1.78 mm) than nonextraction cases (1.00 mm). Swidi et al.[8] also found significantly greater incisor irregularity changes in extraction arches (1.74 mm) compared to nonextraction arches (1.40 mm). The small increases in malalignment is probably the main reason for the lack of significant differences between extraction and nonextraction groups in the present study.

The extraction patients in the present study were significantly older than nonextraction patients when the postretention records were taken. This could be important because Bishara et al.[4] and Bondevik[6] found increases in TSALD between 23-46 years of age. Since the extraction patients were on average 5 years older than nonextraction patients at postretention, the extraction patients had more time for malalignment to worsen. Despite this finding, there were no significant differences in TSALD or incisor irregularity between extraction and nonextraction groups at posttreatment, postretention, or the changes that occurred.

Clinical Implications

1. Orthodontic treatment can be very stable over the long-term.

The average time between posttreatment and postretention records was 17.8 years, which was longer than the 11.2 year average seen in the systematic review by Swidi et al.[8] Despite this duration between records, these cases were extremely stable. The average increase was only 1.07 mm in maxillary incisor irregularity and 1.44 mm in mandibular incisor irregularity. At postretention, 86% of the sample had an incisor irregularity less than 3.5 mm, which is considered to be the limit for clinical significance.

2. This study is not a license for overexpansion.

It must be reemphasized that all cases were treated with conservative, traditional orthodontic principles. Clinicians did not overexpand the transverse dimensions or significantly procline the incisors. All teeth were maintained over basal bone, and canine width was not increased drastically. Since arch dimensions were not changed substantially during treatment, this suggests that a broader arch shape may be inherently more stable, with or without orthodontic intervention.

6. CONCLUSIONS

1. Computed arch shapes were significantly broader in the posterior region for both male arches and nonextraction arches
2. Extraction arches had significantly smaller contact angles, with the smallest between mandibular canines and laterals
3. The posterior arch was correlated with changes in maxillary TSALD, with broader posterior arches undergoing less changes in posttreatment crowding.
4. **Broader posterior arches, together with larger contact angles, indicate more stable arches**
5. Dental arch dimensions were significantly smaller in extraction arches
6. Maxillary TSALD was significantly correlated to maxillary incisor irregularity; mandibular TSALD was significantly correlated to mandibular incisor irregularity
7. There were no significant sex or treatment differences in TSALD or incisor irregularity at T2, T3 or in the changes that occurred
8. Overall, treatment by these clinicians was very stable ($Mx\_II\Delta$ avg = 1.07 mm, $Md\_II\Delta$ avg = 1.44 mm), which may explain why significant differences were not observed between groups. 84% of the sample had incisor irregularity less than 3.5 mm at postretention.

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APPENDIX A

FIGURES

Figure 1. Contact Angles for UR3-2 and LL3-2

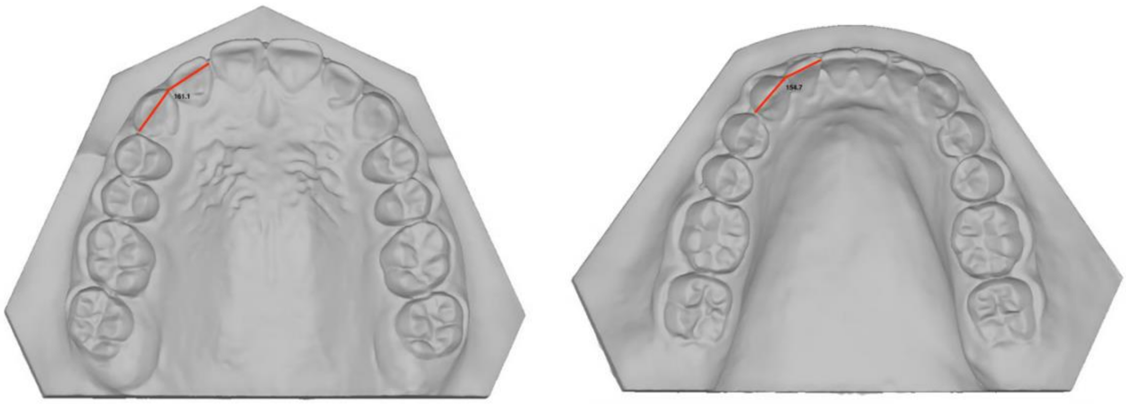


Figure 2. Maxillary and mandibular canine arch depths

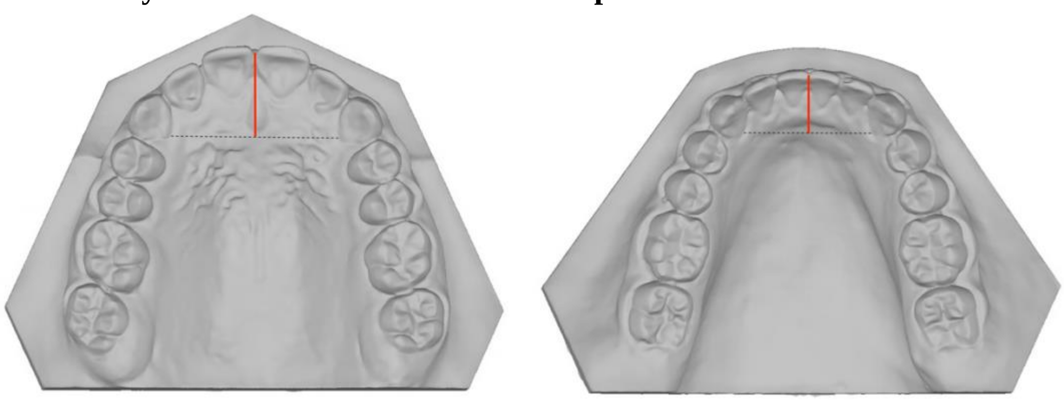


Figure 3. Maxillary and mandibular molar arch depths

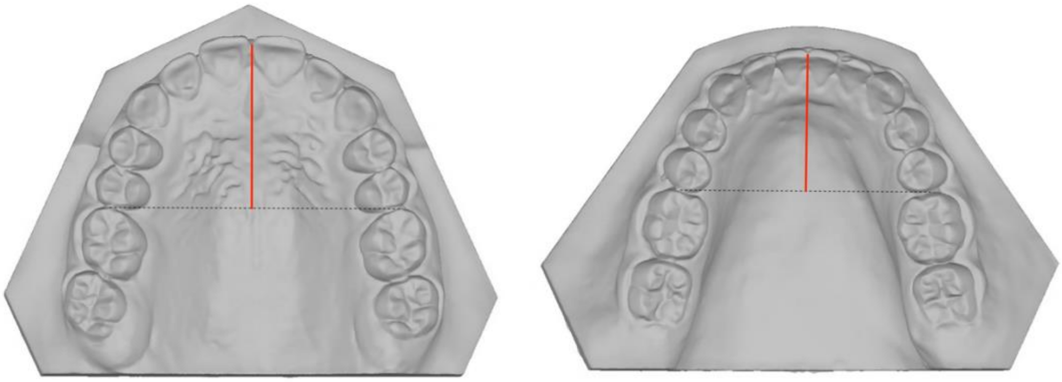


Figure 4. Maxillary and mandibular canine width

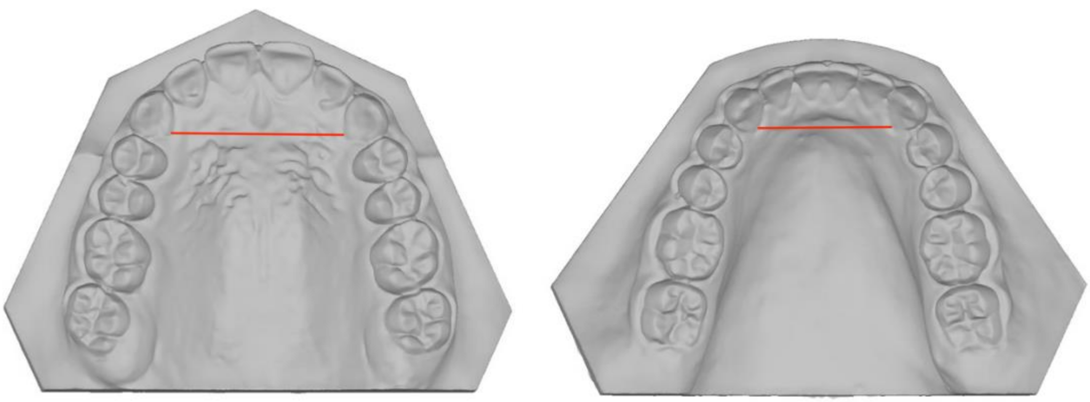


Figure 5. Maxillary and mandibular molar width

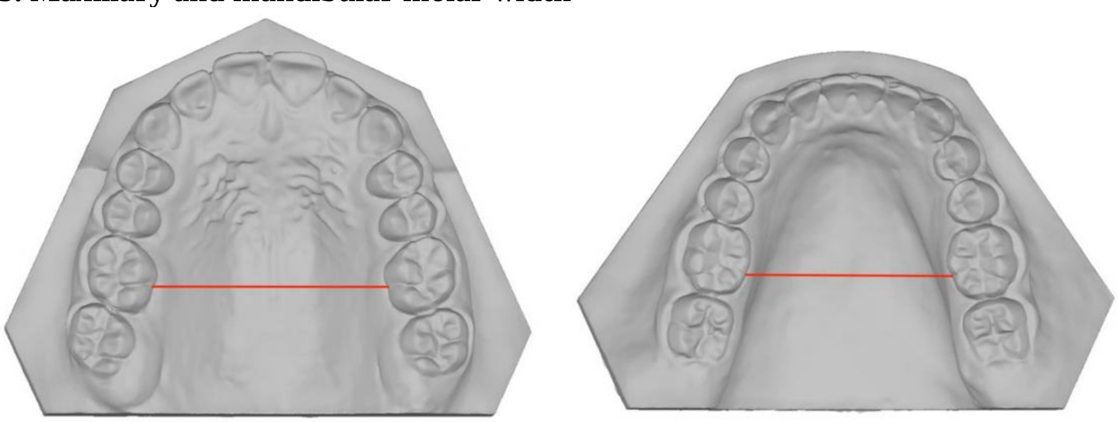


Figure 6. Digitized points for maxillary and mandibular nonextraction arches (extraction arches have two fewer premolar points)

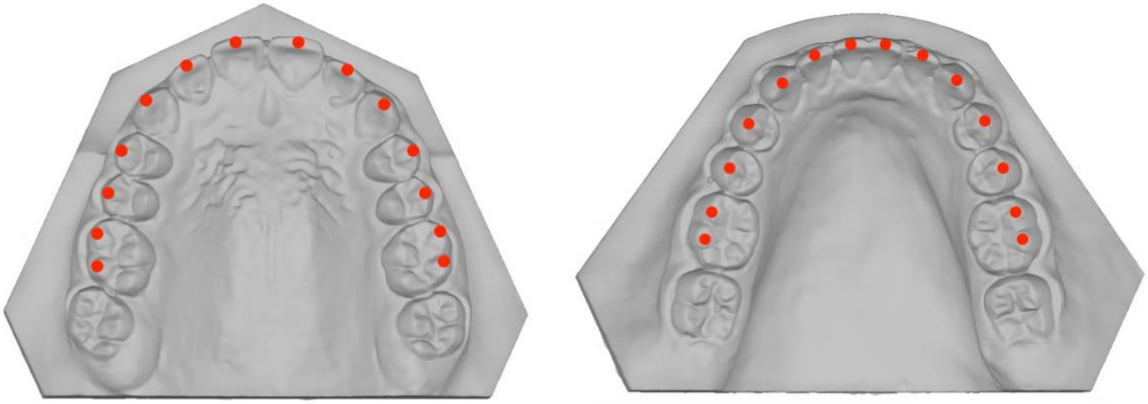


Figure 7. Mean contact angles for the maxillary and mandibular arches

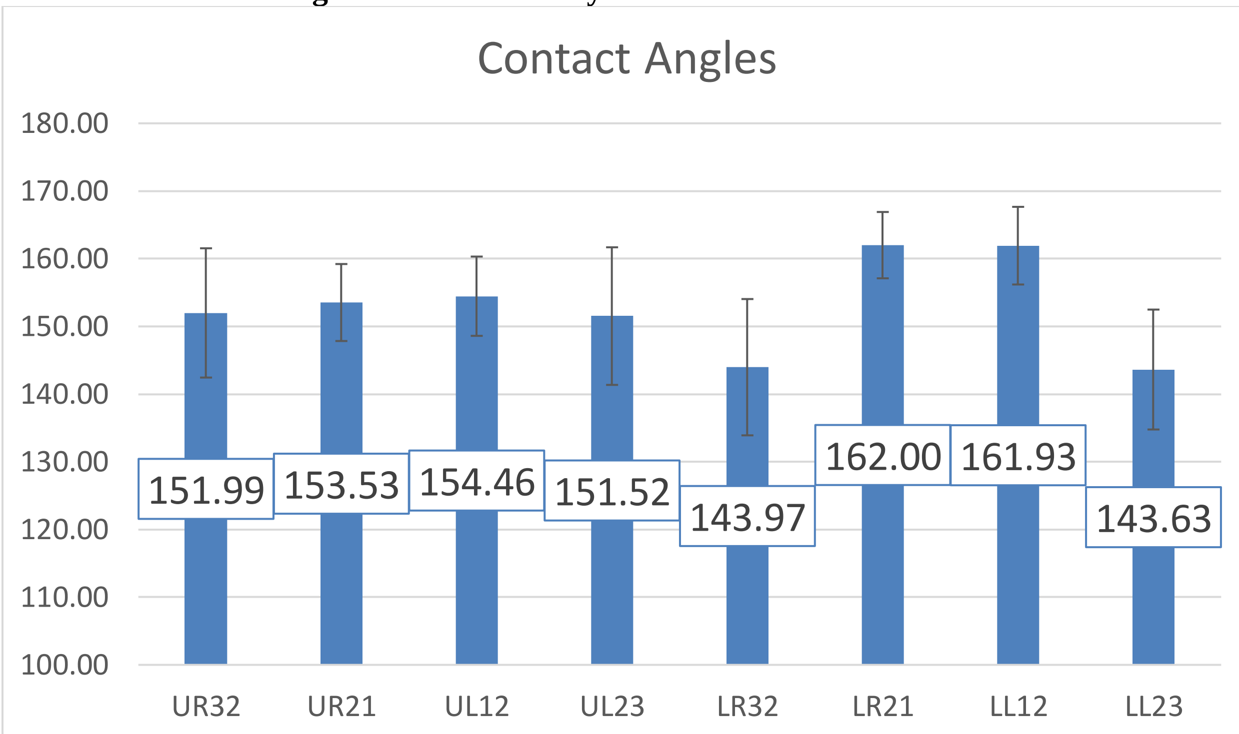


Figure 8. Sex differences in arch shapes computed from polynomials

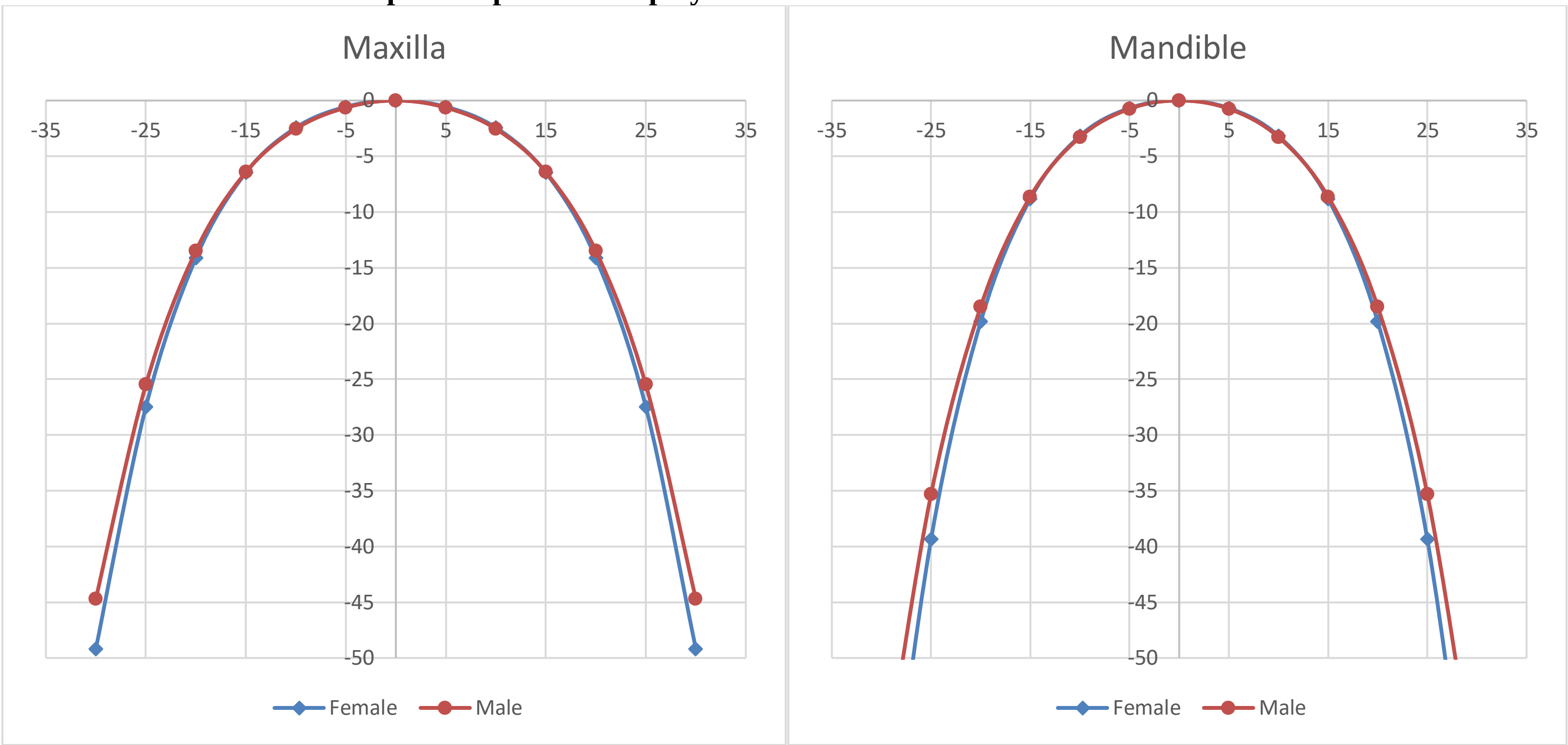


Figure 9. Treatment group differences in arch shapes computed from polynomials

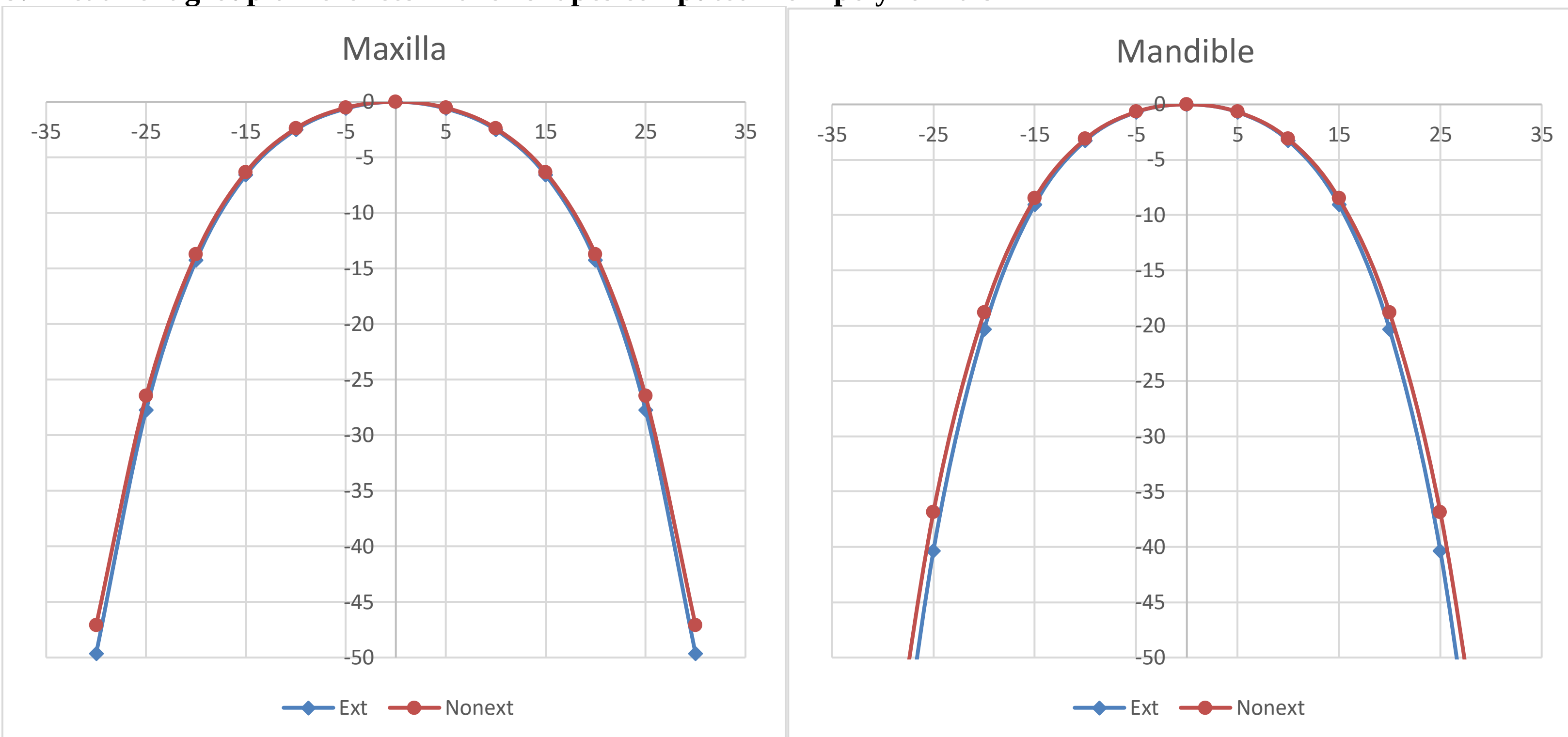


Figure 10. Variation in maxillary extraction arch shapes

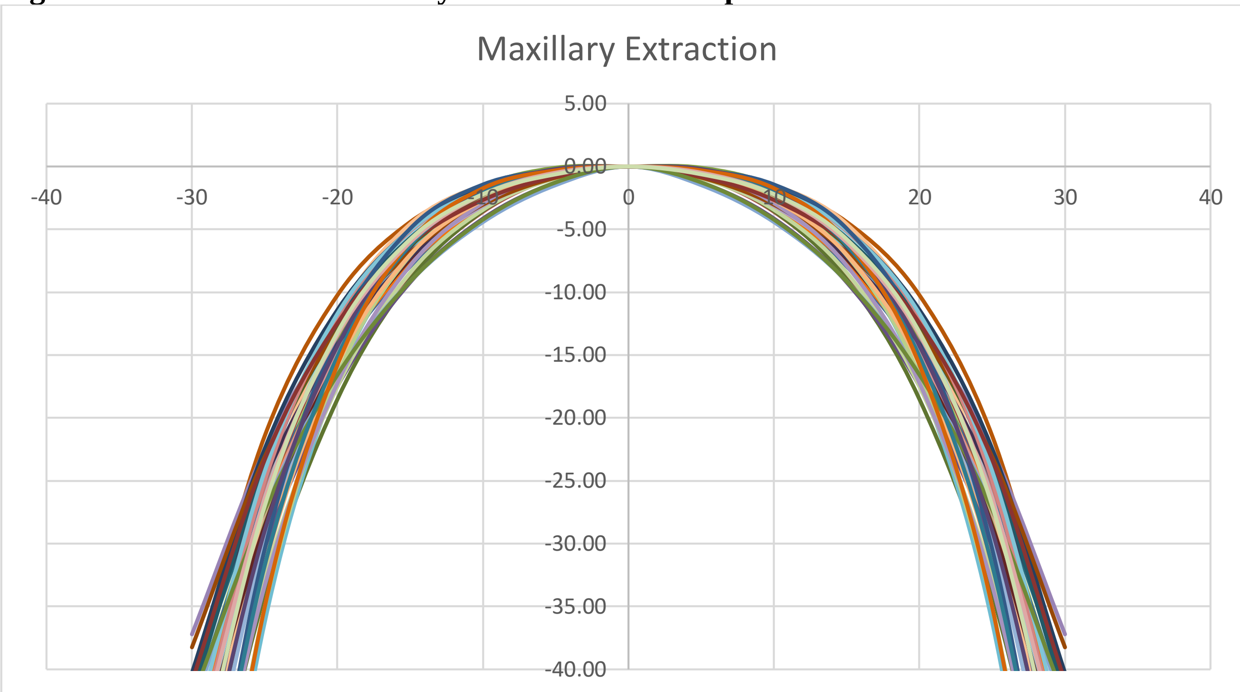


Figure 11. Variation in maxillary nonextraction arch shapes

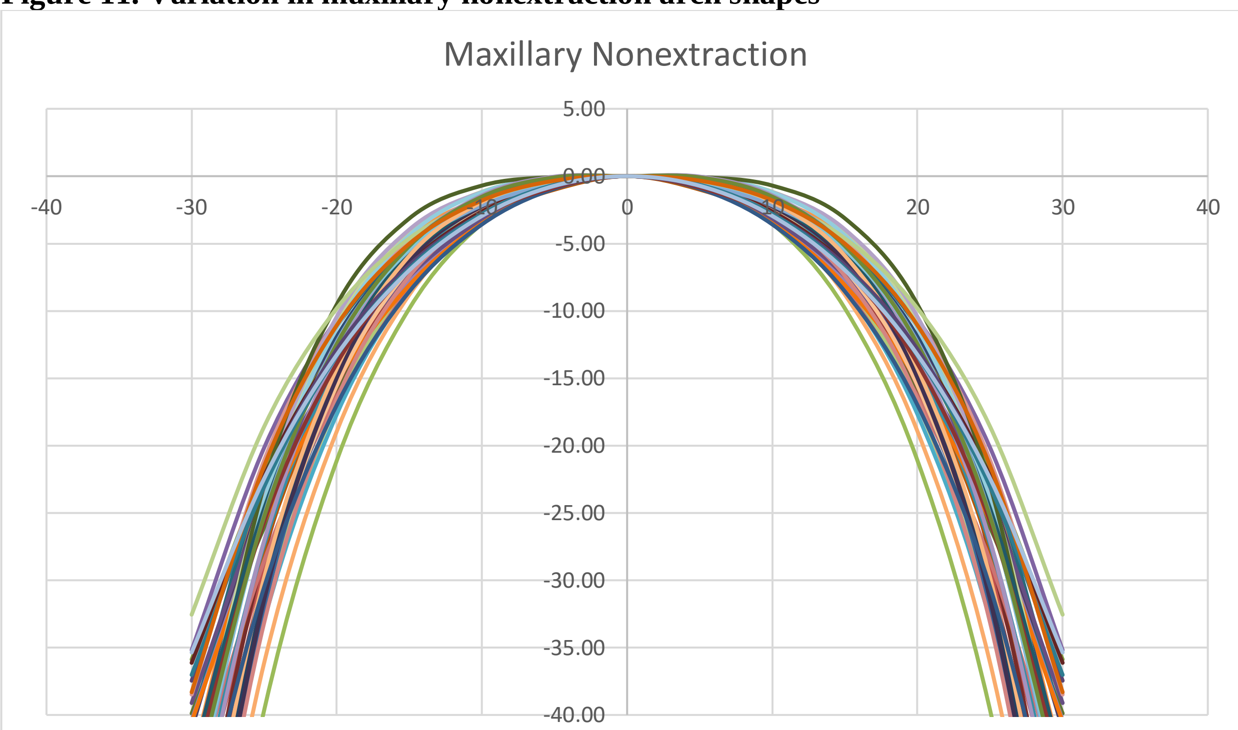


Figure 12. Variation in mandibular extraction arch shapes

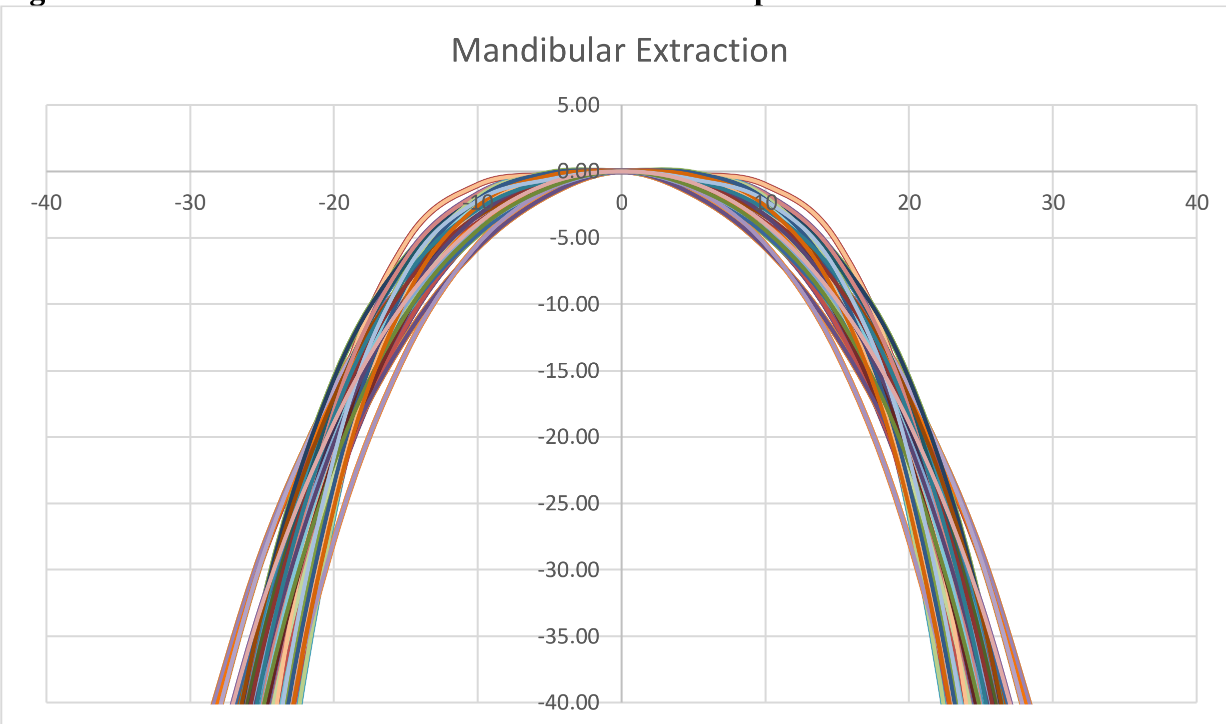


Figure 13. Variation in mandibular nonextraction arch shapes

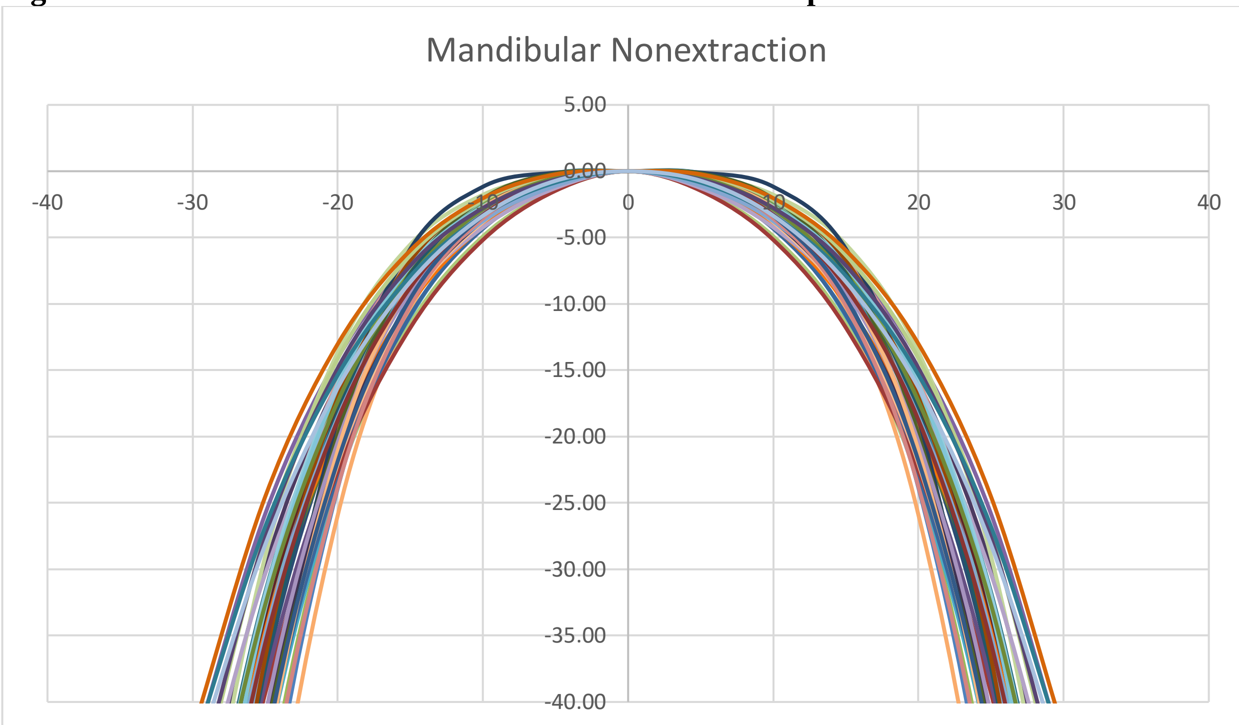


Figure 14. Variation in maxillary female arch shapes

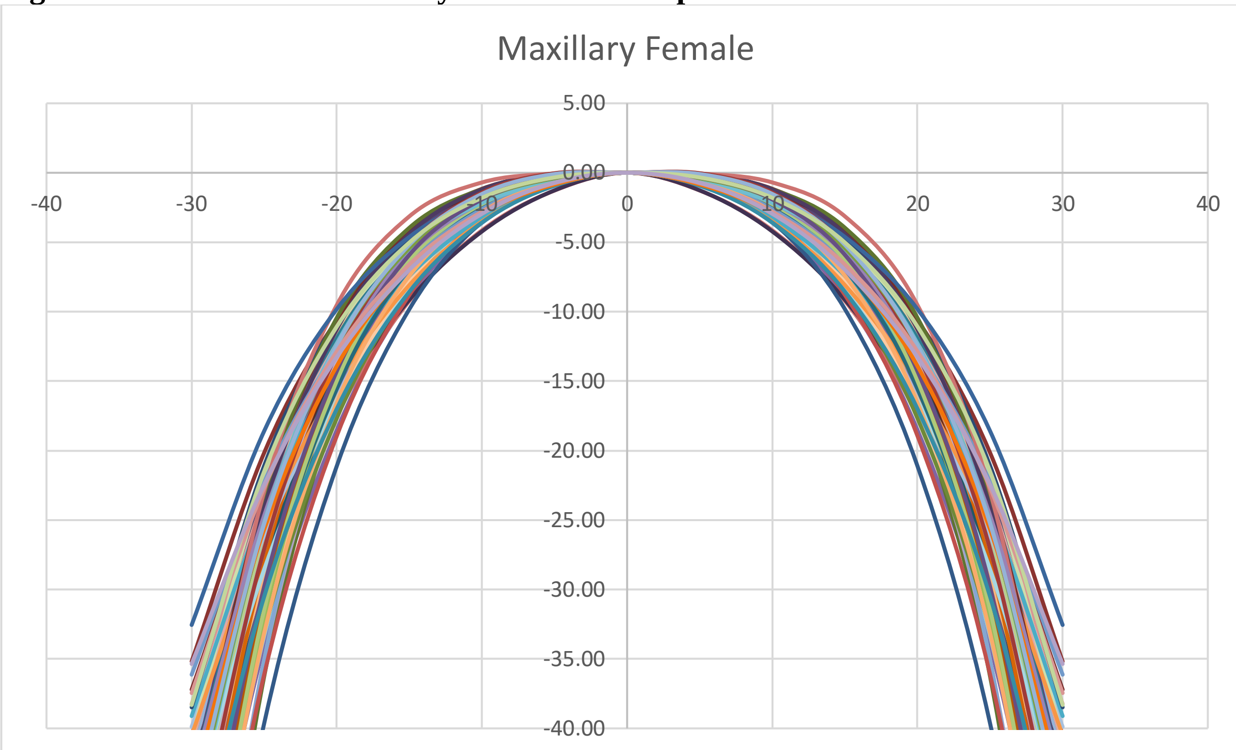


Figure 15. Variation in maxillary male arch shapes

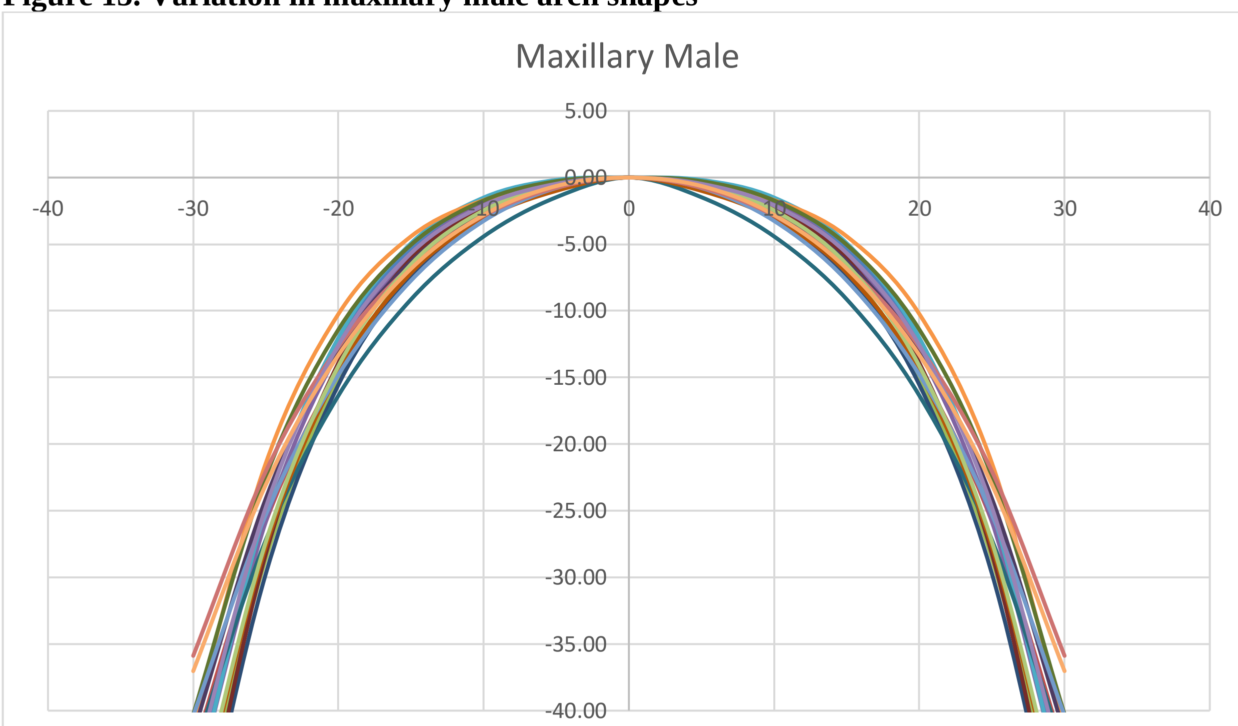


Figure 16. Variation in mandibular female arch shapes

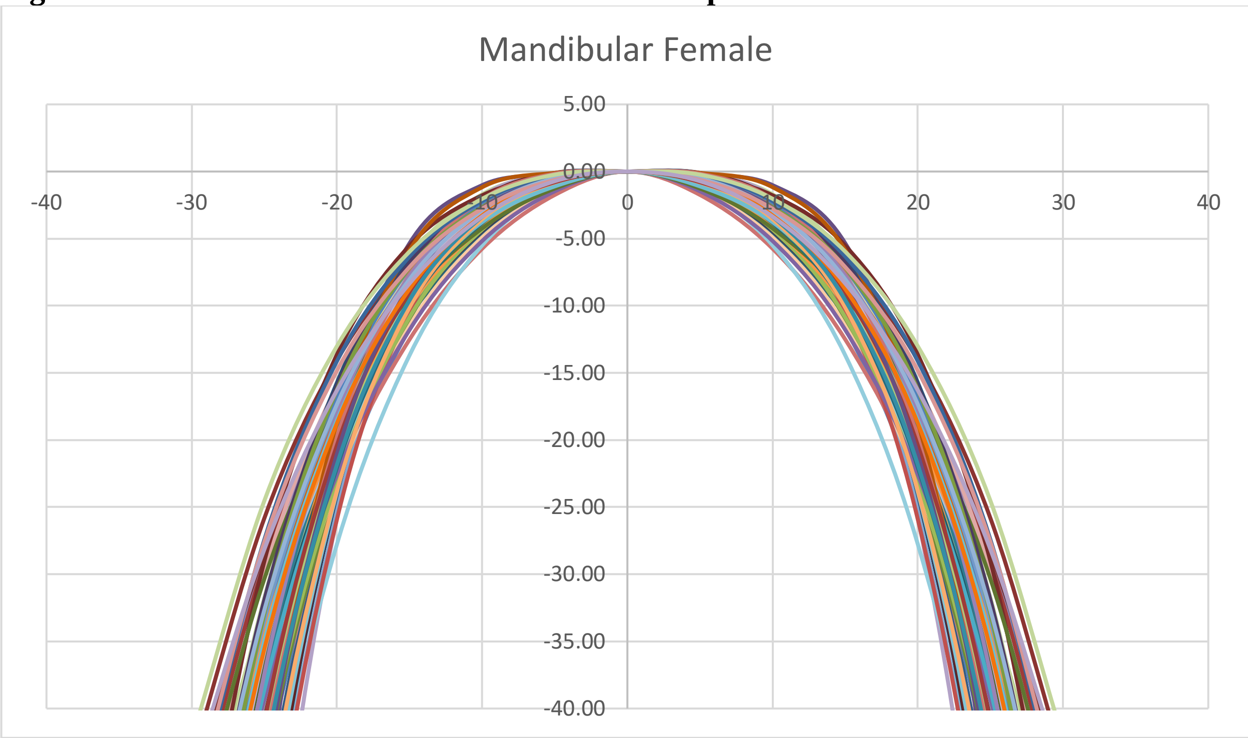
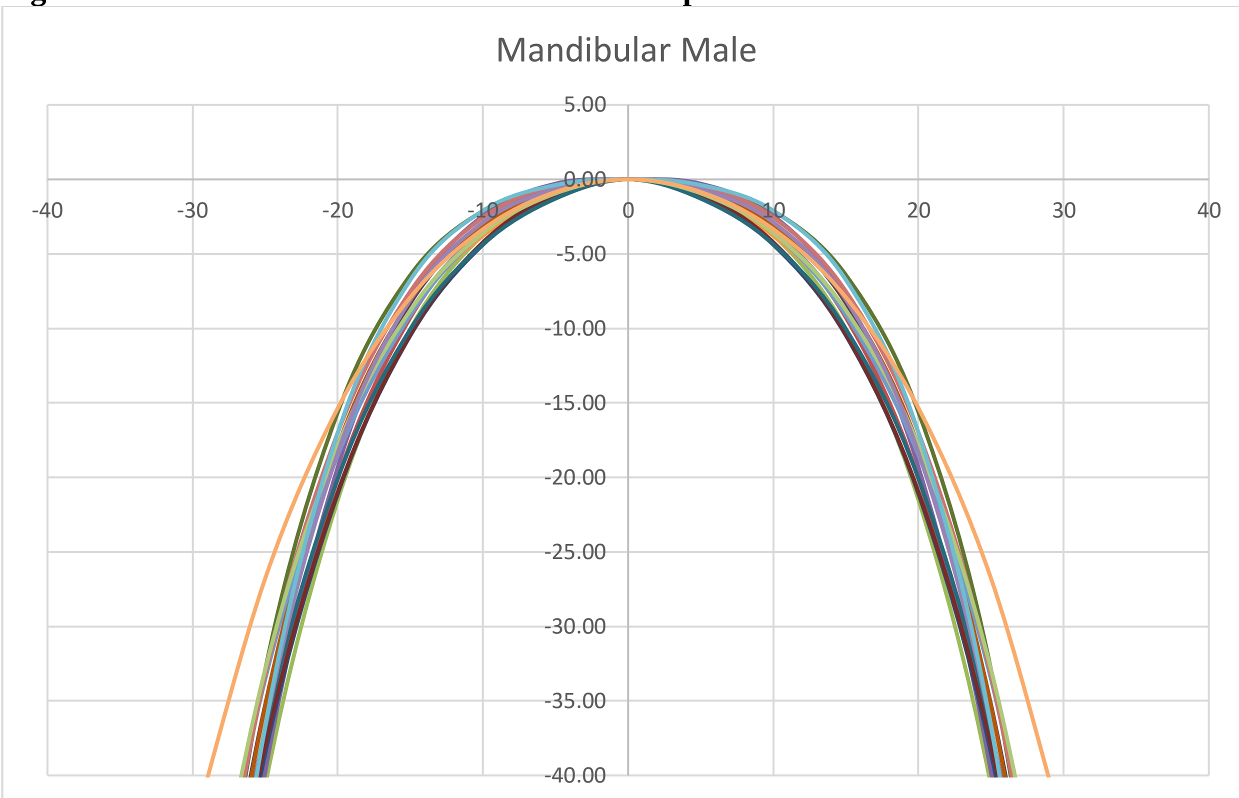


Figure 17. Variation in mandibular male arch shapes



APPENDIX B

TABLES

Table 1. Group differences in patient ages at T2 (posttreatment) and T3 (postretention)

	Extraction		Nonextraction		Difference
	Mean (Years)	**SD**	**Mean (years)**	**SD**	**P value**
T2	16.04	3.5	15.05	2.6	0.111
T3	35.85	7.3	30.75	7.2	**0.001**

Table 2. Sex differences in TSALD and II at T2, T3, and the changes that occured

	Males		Females		Difference
Variable	Mean	SD	Mean	SD	P value
Maxillary TSALD T2	-0.03	0.36	-0.04	0.32	0.918
Mandibular TSALD T2	0.11	0.21	0.06	0.36	0.592
Maxillary II T2	1.01	0.99	0.85	0.81	0.481
Mandibular II T2	0.90	0.55	0.97	0.64	0.659
Maxillary TSALD T3	0.12	0.62	0.19	0.63	0.702
Mandibular TSALD T3	0.98	0.85	0.79	0.76	0.339
Maxillary II T3	2.12	1.26	1.91	1.36	0.557
Mandibular II T3	2.26	1.59	2.42	1.63	0.691
Maxillary TSALD Δ	0.15	0.68	0.22	0.71	0.696
Mandibular TSALD Δ	0.87	0.93	0.73	0.73	0.466
Maxillary II Δ	1.11	1.36	1.06	1.18	0.874
Mandibular II Δ	1.36	1.59	1.45	1.48	0.805

Table 3. Treatment group differences in TSALD and II at T2, T3, and the changes that occured

	Extraction		Nonextraction		Difference
Variable	**Mean**	**SD**	**Mean**	**SD**	**P value**
Maxillary TSALD T2	0.02	0.37	-0.09	0.26	0.089
Mandibular TSALD T2	0.06	0.39	0.08	0.28	0.782
Maxillary II T2	1.00	0.87	0.75	0.80	0.140
Mandibular II T2	0.97	0.62	0.94	0.63	0.826
Maxillary TSALD T3	0.32	0.65	0.03	0.57	**0.020**
Mandibular TSALD T3	0.94	0.75	0.70	0.80	0.131
Maxillary II T3	2.12	1.48	1.77	1.15	0.184
Mandibular II T3	2.54	1.62	2.25	1.62	0.376
Maxillary TSALD Δ	0.30	0.73	0.12	0.67	0.208
Mandibular TSALD Δ	0.88	0.76	0.62	0.77	0.099
Maxillary II Δ	1.12	1.30	1.02	1.12	0.666
Mandibular II Δ	1.56	1.56	1.30	1.43	0.386

Table 4. Correlations between TSALD and II

	Maxillary TSALD Δ		Mandibular TSALD Δ		Maxillary II Δ	
	R	P value	R	P value	R	P value
Maxillary TSALD Δ						
Mandibular TSALD Δ	0.203	**0.043**				
Maxillary II Δ	0.485	**<0.001**	0.091	0.368		
Mandibular II Δ	0.222	**0.026**	0.772	**<0.001**	0.174	0.083

Table 5. Sex differences in contact angles

	Males		Females		Difference
Contact Angle	**Mean (˚)**	**SD**	**Mean (˚)**	**SD**	**P value**
UR32	148.49	8.71	152.76	9.60	0.086
UR21	153.11	6.40	153.62	5.56	0.731
UL12	153.74	5.96	154.62	5.86	0.567
UL23	152.19	7.56	151.37	10.68	0.758
LR32	140.36	8.94	144.76	10.18	0.093
LR21	162.28	3.76	161.94	5.13	0.794
LL12	162.12	5.24	161.88	5.87	0.877
LL23	141.33	11.35	144.12	8.21	0.226

Table 6. Treatment group differences in contact angles

	Extraction		Nonextraction		Difference
Contact Angle	**Mean (˚)**	**SD**	**Mean (˚)**	**SD**	**P value**
UR23	150.02	10.37	154.04	8.23	**0.035**
UR12	153.11	6.01	153.96	5.36	0.462
UL12	153.16	6.03	155.81	5.41	**0.023**
UL23	149.00	9.41	154.15	10.34	**0.011**
LR23	139.29	8.67	148.84	9.13	**<0.001**
LR12	161.24	5.38	162.80	4.25	0.113
LL12	163.06	5.69	160.74	5.60	**0.042**
LL23	140.70	6.06	146.67	10.25	**0.001**

Table 7. Sex differences in dental arch dimensions

	Males		Females		Difference
Arch Dimension	**Mean (mm)**	**SD**	**Mean (mm)**	**SD**	**P value**
Maxillary Canine Width	25.28	1.74	24.33	1.36	**0.013**
Maxillary Canine Depth	13.31	0.86	12.94	1.04	0.173
Maxillary Molar Width	33.48	2.51	33.05	2.78	0.543
Maxillary Molar Depth	24.78	2.72	24.92	3.11	0.865
Mandibular Canine Width	20.42	1.42	19.78	1.18	**0.05**
Mandibular Canine Depth	9.68	0.82	9.06	0.83	**0.005**
Mandibular Molar Width	31.26	2.47	30.84	2.81	0.558
Mandibular Molar Depth	20.81	3.2	20.7	3.2	0.903

Table 8. Treatment group differences in dental arch dimensions

	Extraction		Nonextraction		Difference
Arch Dimension	**Mean (mm)**	**SD**	**Mean (mm)**	**SD**	**P value**
Maxillary Canine Width	24.82	1.56	24.16	1.32	**0.025**
Maxillary Canine Depth	13.3	0.95	12.7	1	**0.003**
Maxillary Molar Width	31.45	1.96	34.87	2.3	**<0.001**
Maxillary Molar Depth	22.27	1.22	27.63	1.55	**<0.001**
Mandibular Canine Width	20.27	1.2	19.5	1.18	**0.002**
Mandibular Canine Depth	9.08	0.75	9.26	0.96	0.28
Mandibular Molar Width	28.98	1.7	32.89	2.14	**<0.001**
Mandibular Molar Depth	17.87	1.11	23.64	1.5	**<0.001**

Table 9. Sex differences in dental arch ratios

	Males		Females		Difference
Dental Arch Ratio	**Mean (%)**	**SD**	**Mean (%)**	**SD**	**P value**
Maxillary Canine Width:Depth	190.70	17.34	189.12	18.57	0.741
Maxillary Molar Width:Depth	136.03	12.18	133.85	13.47	0.528
Mandibular Canine Width:Depth	212.71	26.23	220.59	27.59	0.271
Mandibular Molar Width:Depth	152.02	13.52	151.22	18.27	0.861

Table 10. Treatment group differences in dental arch ratios

	Extraction		Nonextraction		Difference
Dental Arch Ratio	**Mean (%)**	**SD**	**Mean (%)**	**SD**	**P value**
Maxillary Canine Width:Depth	187.43	17.28	191.46	19.22	0.273
Maxillary Molar Width:Depth	141.57	10.83	126.62	11.04	**<0.001**
Mandibular Canine Width:Depth	225.00	24.19	213.10	29.39	**0.029**
Mandibular Molar Width:Depth	162.73	12.63	139.76	13.66	**<0.001**

Table 11. Rotated factor scores

	Maxilla		Mandible	
Rotated Component	**Factor 1**	**Factor 2**	**Factor 1**	**Factor 2**
10mm	0.005	0.993	-0.130	0.984
15mm	0.299	0.952	0.304	0.950
20mm	0.714	0.695	0.847	0.527
25mm	0.956	0.292	0.995	0.097
30mm	0.996	0.002	0.990	-0.113
Variance Explained (%)	71.021	28.328	63.044	36.295
Total Variance Explained (%)		99.349		99.339

Table 12. Sex differences in multivariate factor scores

	Males		Females		Difference
Analysis, Factor Score	**Mean**	**SD**	**Mean**	**SD**	**P value**
Maxillary Anterior (1,2)	-0.109	0.953	0.023	1.014	0.623
Maxillary Posterior (1,1)	0.322	0.489	-0.068	1.067	0.145
Mandibular Anterior (2,2)	-0.035	0.803	0.008	1.043	0.870
Mandibular Posterior (2,1)	0.451	0.440	-0.100	1.062	**0.001**

Table 13. Treatment group differences in multivariate factor scores

	Extraction		Nonextraction		Difference
Analysis, Factor Score	**Mean**	**SD**	**Mean**	**SD**	**P value**
Maxillary Anterior (1,2)	-0.065	0.993	0.068	1.013	0.512
Maxillary Posterior (1,1)	-0.052	1.139	0.054	0.840	0.601
Mandibular Anterior (2,2)	-0.119	1.043	0.122	0.950	0.232
Mandibular Posterior (2,1)	-0.223	1.039	0.228	0.913	**0.024**

Table 14. Pearson product correlations relating alignment and multifactor component scores

	Maxillary				Mandibular			
	TSALD Δ		II Δ		TSALD Δ		II Δ	
Analysis, Factor Score	**R**	**P value**	**R**	**P value**	**R**	**P value**	**R**	**P value**
Maxillary Anterior (1,2)	-0.115	0.258	0.055	0.589	-0.121	0.234	-0.062	0.543
Maxillary Posterior (1,1)	-0.303	**0.003**	-0.195	0.054	-0.009	0.930	0.039	0.699
Mandibular Anterior (2,2)	0.048	0.638	0.030	0.769	0.040	0.692	0.038	0.709
Mandibular Posterior (2,1)	-0.238	**0.018**	-0.129	0.205	-0.060	0.555	0.013	0.900